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Influence of aspect ratio and orientation on large courtyard thermal conditions in the historical centre of Camagüey-Cuba

José Rodríguez-Algeciras [a, b, *], Abel Tablada [c], Mabel Chaos-Yeras [a], Guillermo De la Paz [a], Andreas Matzarakis [d, e]

[a] Department of Architecture, University of Camagüey, Cuba
[b] Architecture Technical School of Barcelona, Spain
[c] Department of Architecture, National University of Singapore, Singapore
[d] Albert-Ludwigs-University Freiburg, Germany
[e] Research Center Human Biometeorology, Deutscher Wetterdienst, Germany

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ABSTRACT

The combined effect of climate change and Urban Heat Island (UHI) effect is leading to a rise in air temperature in urban areas, including those with heritage value. Urban morphology and its effect on sun shading conditions in tropical cities is crucial to reduce UHI and improve outdoor thermal comfort. This paper presents a temporal-spatial analysis of the effect of courtyards geometry on their outdoor thermal conditions in a warm-humid climate. The assessment is based on numerical simulations of the mean radiant temperature, by using the RayMan model. Large courtyards geometry (convent typology), in the historical centre of Camagüey, were modelled and analysed changing their height-to-width ratio and orientation. Our findings confirm the effect of varying courtyard tridimensional aspect ratios on outdoor thermal conditions. Aspect ratios higher than 1 are advisable, as they contribute to improve the courtyard thermal conditions in summer, by reducing the subzones in the courtyard where the Tmrt is above 45 °C. Orienting the courtyard's long axis away from the East-West results in a lower level of Tmrt, with reductions of up to 15.7 °C, for high aspect ratios. The obtained Tmrt patterns give information about the most suitable subzones within the courtyards, according to the time of day and season. The proposed design and usability recommendations could be included in renovation projects aimed at enhancing courtyards' thermal conditions and contributing to an improvement of the surrounding urban microclimate.

1. Introduction

Adapting urban structures to the gradual rise in air temperatures as a consequence of climate change and the Urban Heat Island (UHI) phenomenon is crucial to ensure the livability and health conditions in cities. This is more relevant in historical urban areas, which were built for different climatic and demographic conditions and periods. Architectural design and building retrofitting play a decisive role in determining thermal bioclimatic conditions, both inside and around buildings, especially in compact cities. However, acceptable thermal conditions are sometimes not fully considered by urban planners and architects [1–4]. The parameters which greatly influence urban thermal conditions are wind speed and radiation fluxes (in terms of mean radiant temperature for human-biometeorological studies) [5–9]. Mean radiant temperature (Tmrt) is defined as the “uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure” [10].

Different studies have demonstrated that urban structures can modify these parameters, and therefore, have a stabilizing effect on outdoor thermal comfort. Moreover, the aspect ratio (height/width proportions) and orientation have been identified as design parameters that are crucial to the bioclimatic performance of urban structures [11–25].

* Corresponding author. Department of Architecture, University of Camagüey, Cuba.

E-mail addresses: joserodriguezalgeciras@gmail.com (J. Rodríguez-Algeciras), abel@nus.edu.sg (A. Tablada), mabel.yeras@reduc.edu.cu (M. Chaos-Yeras), guillermo.paz@reduc.edu.cu (G. De la Paz), andreas.matzarakis@dwd.de (A. Matzarakis).

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A courtyard is an architectural element commonly applied as a microclimate modifier for its environmental potentials [16,26]. It is defined as an enclosed space which is delimited by buildings and open above [27]. Literature related to courtyards mainly examines physical features (e.g. geometrical configurations, orientations, proportions and formal design variants) and environmental features (e.g. natural ventilation, thermal performance and thermal comfort conditions) for different climatic regions. As shown in Table 1, most of them were conducted for temperate climates (e.g. Rome-Italy, Chicago, and De Bilt-Netherlands), warm-humid climates (e.g. Antalya-Turkey, Miami, Kuala Lumpur-Malaysia, and Havana-Cuba) and hot-dry climates (Cairo-Egypt, Phoenix-United States of America, and Diyarbakir-Turkey). However, deepening the knowledge on the thermal performance of courtyards in warm-humid climates is still required [27] especially in the case of large courtyards. Moreover, most of those investigations focus on single parameters, such as, solar access, shading factor, surface temperature, wind movements, air temperature, air humidity, or the energy consumption of buildings. There is a predominance of theoretical studies using RayMan and ENVImet to perform numerical simulations, especially on hot summer days. Other studies are based on measurements of a courtyard's climatic conditions and their impact on indoor comfort [28]. In general, most of these researches provided preliminary recommendations on courtyard typologies, showing the great influence of architectural geometries on thermal environmental conditions through single climatic parameters. To date, most relevant studies on this issue suggest some general rules for an efficient courtyard design (to be carefully tested for each specific case) (Table 1):

- *Among all geometric parameters, the height of the courtyard is found to be the most influencing on the courtyard thermal environment. The optimum courtyard height during the year is found to be two-storey for hot dry and temperate climates, one-storey in a cold climate, and three-storey for hot humid climates,*
- *In tropical climates, the increment of height of courtyard enclosure reduces air temperature inside the courtyard as well as in the rooms located on the periphery of the courtyard. However, too deep and enclosed courtyards could also reduce natural ventilation potential having an overall negative effect on thermal comfort.*
- *In a hot-dry climate, an orientation between the N-S axis and the NE-SW axis would be recommended. In a hot-humid climate, placing the long axis of the courtyard along the NE–SW would be recommended for an efficient performance of the shading index. In temperate and cold climates, an orientation around the N-S axis would be recommended.*
- *Inspection of empty, enclosed courtyards in hot-arid climates has demonstrated that a rectangular courtyard with E–W orientation has the least shade. The addition of trees or/and galleries may improve outdoor comfort.*
- *In temperate climates, an E-W orientation provides the longest duration of direct solar radiation, and the N-S direction the shortest, at the centre of courtyards.*

In accordance with the aspects previously covered, well designed courtyards can be an appropriate architectonic solution in most climatic conditions, giving the opportunity to improve users' thermal comfort and their quality of life. However, the influence of aspect ratio, orientation of the shading and thermal conditions of large courtyards, have not been sufficiently investigated in tropical warm-humid climates. Therefore, two main objectives have been defined in this study related to the contribution of geometrical characteristics of large courtyards in Camagüey-Cuba on human thermal conditions, especially during the summer:

1) *Perform a spatial-temporal analysis on the thermal conditions of large courtyards, focusing on the relationship between aspect ratio, orientation and mean radiant temperature in the warm-humid climate of Camagüey-Cuba.*
2) *Suggest design and usability recommendations for the studied large courtyards, suitable to reduce extreme thermal conditions exposure from a climate-responsive urban and architectural design perspective.*

Moreover, from the parameterisation of mean radiant temperature, the value of this work is focused on two main aspects:

1.1. Theoretical issues

This paper contributes to increase knowledge related to urban morphologies in Cuba, and their influence on urban microclimatic conditions. In addition, it allows comparisons with similar researches in other regions, and provides a knowledge base which can be included in the professional education of designers, urban planners, conservators, and architects.

1.2. Practical application

These findings may be considered in urban renewal projects, aimed at the improvement of outdoor thermal condition in the city through the modification of urban and architectural structures. The design recommendations here provided are useful to local authority planning and conservators.

2. Courtyards in the historical centre of Camagüey

The labyrinthine urban pattern of the city of Camagüey is unique in Latin American urban planning. This peculiar urban form is one of the crucial elements that allowed the declaration of the city as a World Heritage site in 2008 by the United Nations Educational, Scientific and Cultural Organization (UNESCO). The city, founded in 1515, built up a solid urban identity as a blend of forms, volumes and small spaces over the centuries. This complex urban layout is based on a network of squares, of varying sizes, crisscrossed by winding alleys. Two main building typologies define the actual image of the city's architecture: the full-block religious complexes, distinguished by their impact on the urban fabric of the city, and the residential repertoire, which is the most representative and numerous. The architectural typology of the colonial period is highly specific, and courtyards are one of its principals hallmarks [37–40].

The conservation policies currently in place have both rescued and raised a new awareness about Camagüey's rich cultural heritage, customs, traditions and lifestyles. However, it is necessary to implement conservation policies associated with climate issues, to mitigate thermal stress on users and visitors in outdoor environments, such as, courtyards and squares. Courtyards become a key element of environmental comfort in Cuban architecture, allowing access to natural ventilation and sunlight. At the urban scale, large courtyards also influence the urban microclimate in terms of radiation fluxes, wind conditions and the cooling effect of vegetation. As a thermal regulator, protecting from solar radiation and modifying wind patterns, the thermal performance of courtyard is a most necessary research topic in hot and warm-humid climates. The central courtyard serves as an open and lively environment that connects and unifies different subzones of a building, maintains privacy and creates a continuous environment, where people generally perform their daily activities [32,41]. Therefore, architects, renovators and urban designers could use its potentials to create shaded and comfortable environments during the day.

Table 1
Studies on the impact of courtyards geometry on outdoors thermal conditions.

Reference/Climate	Results
[26] Hot humid, Hot dry, Temperate, and Cold climates (Kuala Lumpur, Cairo, Rome and Stockholm)	This paper presents a modelling study carried out into the effect of rectangular courtyard proportions on the shading and exposure conditions produced on the internal envelope of the form in four different climatic regions. Morphology: Square and rectangular courtyards with different depths. Modelling Tool: CourtSun program Indicators: Shading index. Results: The study suggests general rules for efficient courtyard design. • Hot-humid climate: orienting the long axis of the courtyard along the northeast–southwest would be recommended. The optimum courtyard height was found to be three-storey. • Temperate climates: orientation around the north–south axis would be recommended. The optimum courtyard height was found to be two-storey. • Cold climates: orientation around the north–south axis would be recommended. The optimum courtyard height was found to be one-storey. • Hot-dry climate: orientation between the northeast–southwest axis and the north–south axis ensure an efficient performance in both seasons. The optimum courtyard height was found to be two-storey.
[29] Temperate climate (Rome, Italy)	The study focuses on the effect of solar heat gain on the energy demand of courtyard building form with different proportions. Morphology: The ratio R1 is taken as the ratio of the courtyard's floor perimeters P to the form's height H (P/H); it indicates the depth of the form. It ranges between 1 and 10 in one degree steps. The ratio R2 indicates the elongation of the form (width W/length L) it varies between 0.1 and 1 in one degree steps. So, a courtyard form with ratio R2 equal to 0.1 means that the form has, for example, 1 m width and 10 m length. If ratio R1 for this form is 1, the height of the courtyard will be 22 m. Modelling Tool: Virtual Environment (IES) program Indicators: solar heat gain Results: The proportions of the courtyard building considerably influence the need for heating and cooling. It was found that, for the purpose of reducing the cooling load in summer and heating load in winter, deeper courtyard forms were the most preferable. The self-shading of the courtyard building acts to reduce the need for cooling by an average of about 4% whereas, in winter, it has the effect of increasing the heating load by an average of 12%. This indicates that obtaining solar radiation in winter is more critical than avoiding in summer.
[12] Temperate climate (Rome, Italy)	This paper examines the shading performance of polygonal courtyard forms. The study was carried out on summer and winter solstices. Morphology: Polygonal courtyard forms with pentagonal, hexagonal, heptagonal and octagonal plans. Modelling Tool: Computer program to calculate the shaded and sunlit areas based on a set of equations, which were derived through analysing the relationship between the sun location at any time and the courtyard form. Indicators: Shading index. Results: The courtyard proportions and geometry have a considerable influence on the shading performance of courtyard forms. Deep courtyard forms with any geometry are recommended to achieve maximum internal shaded areas in summer. In winter, shallow forms would be advantageous for obtaining sunlit areas. For a reasonable performance throughout the whole year, courtyards with R1 equal to or greater than 5 are recommended. They ensure a significant amount of internal shadows in summer, as well as a considerable sunlit area in winter.
[30] Hot-dry climate (Phoenix, Arizona) Hot-humid climate (Miami, Florida.) Temperate climate. (Chicago, Illinois) Cold climate. (Minneapolis, Minnesota)	In this paper, the energy performance of a central atrium is investigated and compared with the energy performance of a courtyard with the samegeometric proportions. Morphology: Square geometry. Modelling Tool: DOE2.1E program Indicators: Energy performance of atriums and courtyards in buildings Results: The open courtyard building exhibits a better energy performance for the shorter buildings. As the building height increases, however, at some point the enclosed atrium exhibits a better energy performance.
[31] Hot-arid climate (Beer-Sheba, Israel)	The outdoor thermal comfort in an enclosed courtyard has been studied numerically. The effect of wind, and shading by different means – galleries, horizontal shading or trees – has been examined during hot summer day. Morphology: Square and rectangular courtyards. The following three geometries (defined according to East–West length* North–South length) of courtyards surrounded by a 9 m high (three floors) and 12 m wide building were considered: 20 m × 40 m (proportion 1:2), 40 m × 20 m (proportion 2:1), and 28 m × 28 m (proportion 1:1). The recommended heights for these courtyards are: 10 m, 7 m and 9 m respectively. These heights agree with the chosen height, 9 m, to within 2 m. Modelling Tool: Envi-met 3.1 Indicators: The thermal comfort is evaluated by the Predicted Mean Vote (PMV) index. Results: In summer, outdoor comfort is mainly dependent on solar radiation; hence, shading is the best means to improve comfort, while the contribution of wind under all configurations studied was limited and much smaller than the shade contribution. Inspection of empty enclosed courtyards has shown that an elongated E–W rectangular courtyard has the least shade, and therefore it is the most uncomfortable. The addition of trees or/and galleries to the closed courtyard significantly improves the outdoor comfort.
[15] Humid continental climate (Beijing)	This paper presents predicting and understanding temporal 3D exterior surface temperature distribution in an ideal courtyard. Morphology: Square courtyard (constant width = 10 m and variable height).

Table 1 (*continued*)

Reference/Climate	Results
	Modelling Tool: STTC (Surface Thermal Time Constant) model for predicting ground-surface temperature. Indicators: Surface temperature. Results: The results show that increasing courtyard height, thermal mass and material conductivity intensify the nocturnal micro-scale heat island effect in summer. Increasing thermal mass, surface albedo and conductivity efficiently reduce the peak temperature during daytime, which leads to a micro-scale urban cool island phenomenon in winter time. The solar radiation and the urban structures are found to be the most important factors in determining the courtyard thermal environment during both summer (July 1st) and winter (January 1st). Among all 4 parameters that were studied here, the height of the courtyard is found to be the most influencing. The surface albedo has the least influence on the courtyard thermal environment.
[32] Tropical climate (Malaysia)	This study assessed the microclimate performance of a U-shape courtyard in a General Hospital in Malaysia. The study combined experimental and simulation method, followed by the parametric analysis. Morphology: This study tested the effects of changing the courtyard enclosure height to 4 m and 24 m. In relation to the orientation, four scenarios were investigated that represent the main cardinal directions: north, south, east and west. Modelling Tool: Integrated Environmental Solution (IES <VE> software) Indicators: Air temperature, humidity and wind patterns. Results: The result verifies that the manipulation of courtyard configuration and its orientation impact its microclimate modifying ability. The increment of height of courtyard enclosure reduces air temperature inside the courtyard as well as the rooms located at the peripheral of the courtyard. However, the effect of orientation as observed from the recorded air temperature data, shows that the effect is less but significant.
[16] Tropical climate (Malaysia)	This paper focuses on the application of courtyards in the context of Malaysian hospitals. Thirty-two courtyards in 19 hospitals were inventoried. Besides the courtyard functions, design variants were recorded in terms of its form and aspect ratio, courtyard orientation and physical features within the courtyard. Morphology: All design variants. Indicators: Courtyard functions, aspect ratio, orientation and physical features. Results: The results revealed that the courtyards in the Malaysian hospitals buildings are creatively manipulated. The paper concludes with an outline of means to optimize a microclimatic and healing performances. The research has provided a background to support further research and analysis on the impact of courtyard design variants of its performance.
[33] Hot-dry climate (Diyarbakir, Turkey) Hot-humid climate (Antalya, Turkey) Cold climate (Erzurum, Turkey)	The purpose of this study is to examine the energy efficiencies of the courtyard buildings used either as a micro climatic regulator, and to determine courtyard comfort statuses, and thus to provide new information to designers at the process of putting forward the optimum courtyard form according to the characteristics and data of the specific climate for different climatic regions. This study is limited to comparative analyses between seven different yard building options considered for application in plot centers of "Hot-Dry Climate", "Hot-Moist Climate" and "Cold Climate" with different characteristics dominant in Turkey. Morphology: Square and rectangular courtyards (variable width). Modelling Tool: Computational Fluid Dynamics (CFD Fluent 6.3 program) Indicators: Solar heat gains and energy efficienc. Results: The optimum courtyard ratio is a form that allows minimum radiation during summer and maximum radiation during winter. Generally, the effect of shadowing on the required heating load during winter is more than its effect on decreasing the cooling load during summer. Making solar radiation gain during winter is more critical (important) than evading this during summer. It has been observed that the required annual energy demand increases in parallel with the increase in courtyard length.
[34] Tropical climate (Malaysia)	The design variants of courtyard such as plan aspect ratio and cantilevered roofs (as shading devices) have been investigated using CFD in IES<VE> software. Morphology: Square and rectangular courtyards. Modelling Tool: CFD in IES<VE> software Indicators: Three environmental indicators were observed namely air temperature (C°), air velocity (m/s) and the thermal comfort which is evaluated by the Predicted Mean Vote (PMV) index. Results: Aspect ratio and cantilevered roof plays a significant effect on the wind speed and, consequently, the thermal comfort. The U-shape of courtyard with aspect ratio of 1:2 (which is considered as a rectangle) performs better than the U-shape of courtyard with aspect ratio of 1:1 (which is considered as a square). In addition, increasing the shading area using cantilevered roof has shown a remarkable improvement for the thermal comfort.
[35] Temperate climate (De Bilt, Netherlands)	A parametric study into different geometries and orientations of urban courtyard blocks in the Netherlands was therefore conducted for the hottest day. The study also considered the most severe climate scenario for the Netherlands for the year 2050. Three urban heat mitigation strategies that moderate the microclimate of the courtyards were investigated: changing the albedo of the facades of the urban blocks, including water ponds and including urban vegetation. Morphology: Square and rectangular courtyards. The models vary in length and width from 10 to 50 m with steps of 10 m; and have four main orientations N–S, E–W, NW–SE, and NE–SW. Modelling Tool: ENVI-met 3.1 Indicators: Air temperature and mean radiant temperature Results: The results showed that a north–south canyon orientation provides the shortest and the east–west direction the longest duration of direct sun at the centre of the courtyards. Moreover, increasing the albedo of the facades actually increased the mean radiant temperature in a closed

(*continued on next page*)

Table 1 (*continued*)

Reference/Climate	Results
	urban layout such as a courtyard. In contrast, using a water pool and urban vegetation cooled the microclimates; providing further evidence of their promise as strategies for cooling cities.
[27] Tropical climate (Kuala Lumpur, Malaysia)	This study evaluates the ability of unshaded courtyards for providing thermally comfortable outdoor spaces according to different design configurations and scenarios, including the orientations, height and albedo of wall enclosure, and use of vegetation. Morphology: Square courtyards. Variable height Modelling Tool: ENVI-met 3.1 Indicators: Predicted mean vote (PMV) and Physiologically Equivalent Temperature (PET) index Results: Simulations reveal that the courtyard facing North has slightly better thermal performance with minimum air temperature of 300 K at 8:00 and maximum air temperature of 305 K at 15:00. Increasing the height of wall enclosures in courtyards significantly improves the outdoor thermal comfort by blocking the intense solar radiations and providing more shaded areas. PET values reveal that increasing the height of courtyard significantly reduces the duration of thermal discomfort from 9 h (9:00 to 18:00) to 3 h (12:00 to 15:00). As a result, guidelines are proposed in order to optimize the design of courtyards towards enhancing their thermal performance characteristics.
[28] Hot-humid climate (La Habana, Cuba)	This paper first presents an historical overview of the typological evolution of the residential architecture in this part of the city and its relation to natural ventilation and thermal comfort. Based on the historical overview, the measurements and the survey, some preliminary design recommendations for residential buildings in Old Havana are provided. Morphology: Compact urban morphology of Old Havana (Courtyards) Modelling Tool: Field measurements and a limited comfort survey Indicators: Air temperature, relative humidity, wind/air speed, air temperature, radiant temperature, relative humidity, and ET* comfort temperature. Results: Based on the comfort survey, the obtained comfort zone for summer conditions for Old Havana residential buildings ranges from 24.7 to 30.7 °C ET*. The evident way of achieving cross ventilation is with courtyards that are permeable to the exterior environment both from the ground floor and from the top. This more open courtyard configuration allows higher indoor ventilation rates than the one achieved in buildings with a single narrow courtyard which are only open at the top. In cases of wide courtyards, additional solar protection should be provided.
[4] Oceanic climate, Temperate continental climate, Temperate subcontinental climate, Subcoastal climate, Temperate-hot climate, subtropical climate (Italy)	The study carries out a theoretical investigation of the influence of height/width (H/W) proportions to the thermal comfort of court- yards, for Italian climate zones. Morphology: Square courtyards. Variable height Modelling Tool: RayMan Indicators: Physiologically Equivalent Temperature (PET) index Results: The results indicate that high height/width proportions appear to have a stabilizing effect over thermal comfort, for both winter and summer season. As a general rule, to be carefully tested for each specific case, higher H/W proportions of 4:5 to 5:5 may be suggested for warmer climates, while lower-medium H/W proportions of 3:5 to 4:5 could be suitable for colder climates.
[36] Temperate climate (Netherlands)	In this paper, singular East-West and North-South, linear East-West and North-South, and a courtyard form were analysed for the hottest day so far in the temperate climate of the Netherlands. Morphology: The three main urban forms studied (singular, linear and courtyard), each with a different compactness, provide different situations in their microclimate. Modelling Tool: ENVI-met 3.1, RayMan model Indicators: Physiologically Equivalent Temperature (PET) index Results: This paper shows that the courtyard provides the most comfortable microclimate in the Netherlands in June compared to the other studied urban forms. The courtyard provides a more protected microclimate which has less solar radiation in summer. Since courtyards are not yet very common in temperate climates, the changing global climate, with an expected increase of temperature levels in Western Europe, advocates the usage of courtyards in (new or redeveloped) urban settings.

Several typologies have been adopted for courtyard design in different climatic regions. The history of using courtyards in Cuba goes back to the Spanish colonization period, where enclosed inner courtyards were incorporated in every building, based on the influence of southern Spanish and Moorish architecture [42]. The footprint of the most representative courtyards in the historical urban centre of Camagüey, is generally associated to large buildings, most of them with a religious character, in comparison with the more traditional single-storey dwellings. Together with a church and a square, they constitute an urban complex. As shown in Fig. 1, these courtyards are generally square (around 400 m^2–900 m^2), enclosed and open above. Due to their large dimensions and low height, they lack adequate sun protection when vegetation is not prominent. Based on this description, study models were designed to perform simulations and analyse the thermal conditions of large courtyards in Camagüey, Cuba.

3. Material and methods

3.1. Location and climate

The study was conducted in Camagüey (21° 23′ N, 77° 50′ W) (Fig. 2) which has a climate type AW (tropical savannah) [43]. The average annual temperature is 25.2 °C, with 78% mean relative humidity. June, July and August are the hottest months, with a mean temperature of 29 °C during the daytime (between 09:00 h and 17:00 h). Whereas, December, January and February are the coldest months with a mean temperature of 24 °C between 09:00 h and 17:00 h. Prevailing winds come from the east, with speeds averaging around 3.5 ms^{-1}. The average annual rainfall is approximately 1400 mm. The weather station OMM 783550 located at the airport of the city of Camagüey was selected to collect this climatic data. Mean values of air temperature, relative humidity, solar

Fig. 1. Representative religious complexes of historical urban centre of Camagüey [40]. Geometrical configuration of its large courtyards.

radiation and wind speed, for a typical winter and summer day were used with a time resolution of 1 h, as input parameters for the RayMan model [44]. Wind speed measured at 10 m above ground level was reduced to the height of 1.1 m according to the generally adopted empirical formula [45,46](Eq. (1)):

$$WS_{1.1} = WS_h * (1.1/h)^{\alpha} \; \alpha = 0.12 * z_0 + 0.18 \quad (1)$$

(WS_h): wind speed at 10 m from the ground

(α): empirical exponent which depends on the surface roughness

(z_0) is the roughness length

The values ($\alpha = 0.30$) and ($z_0 = 1$) correspond to the walls' characteristics of the selected courtyards in the study area. A cloudless sky was assumed in the simulations.

3.2. Methodology

Quantitative information on different spatial and temporal

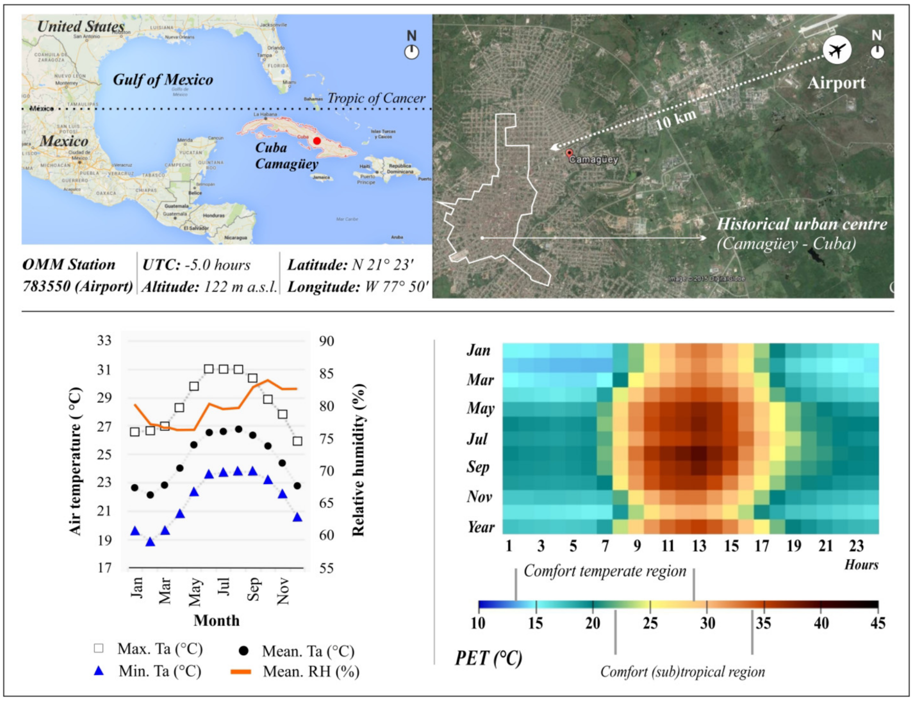


Fig. 2. Climate conditions of the study area.

scales is required for an assessment of outdoor thermal conditions. The mean radiant temperature is one of the most important meteorological parameters that governs human energy balance in outdoor environments [47–50]. Besides, numerous researches confirm that Tmrt is often a better parameter, when compared to air temperature, to assess human thermal comfort in outdoor environments [48,51,52], because it provides more accurate estimates about the impacts of climate on human health, than using air temperature alone [53].

The integral radiation measurements, as the most accurate method for obtaining Tmrt, is relatively expensive, therefore, numerical modelling by using three-dimensional microclimate models is increasingly more used. Calculating Tmrt from models, depends on the input meteorological parameters used, morphological factors and how their interactions will interfere with wind speed and solar radiation in a microscale. An alternative approach, is based on output of RayMan, using meteorological parameters, such as, global solar radiation (or cloud cover data), relative humidity (or vapour pressure), wind speed and air temperature [54]. During the daytime, the physiologically equivalent temperature (PET) is strongly governed by Tmrt [9], therefore the modifications to urban structures and hence, the solar access, has a strong impact on the resultant Tmrt and PET. For Camagüey's average meteorological variables, on the analysed periods, Tmrt values above 45 °C correspond to heat thermal stress levels (PET values over 30 °C), according to thermal perception classifications obtained for the (sub)tropical climate region of Sun Moon Lake (in central Taiwan, 23°52′N, 120°55′E) [55]. It should be noted that the same thermal conditions might be perceived differently due acclimatization and adaptation to the heat. However, the same threshold value of Tmrt for heat (Tmrt ≥ 45 °C) was used as the assessment criteria to make cross-courtyard comparison and discuss our results.

This study uses the morphology of four large courtyards, in the historical centre of Camagüey (Fig. 1), as reference to build the models for simulation. Based on their proportions and orientations, two three-dimensional models, with constant floor plan dimensions, were created. Fig. 3 illustrates the cases considered and lists the simulation conditions. The simulations focused on solar access and their impact on thermal conditions in terms of Tmrt, to provide urban recommendations related to design and courtyard use. In addition, a partial analysis of the PET index under summer conditions is included. The distribution of sunshine hours and the cumulative solar radiation during the day, were obtained in Heliodon2 (www.heliodon.net), which is a free software for the interactive design of solar radiation in architectural and urban projects. In addition, the RayMan model was employed to examine the spatial and temporal variations of Tmrt, as an indicator of outdoor heat stress in hot-humid climate.

The RayMan model was developed according to Guideline 3787 of the German Engineering Society [49], and calculates the radiation flux densities and Tmrt [56]. The main advantage of RayMan is that it facilitates the reliable determination of the microclimatological modifications of different urban environments, since the model considers the radiation modification effects of the complex surface structure very precisely [44,48,56]. RayMan model is compatible with Microsoft Windows, and requires input data on personal parameters, on surface morphological conditions of the study area, and on basic meteorological data (e.g. air temperature, air humidity and wind speed) for the calculation of radiation fluxes and common thermal indices for the thermal human-bioclimate. Another advantage of the model is the short running time in comparison with other models [44]. RayMan is suitable for several applications in urban areas such as health, tourism, landscape and ecological planning, urban planning and street design, and is available for general use under http://www.mif.uni-freiburg.de/rayman) with an easy user-friendly interface [44,48]. This model has been validated for urban thermal comfort studies in several climatic regions [4,25,54,57–63].

Solar radiation was simulated for the summer and winter solstices to account for the longest and shortest days. However,

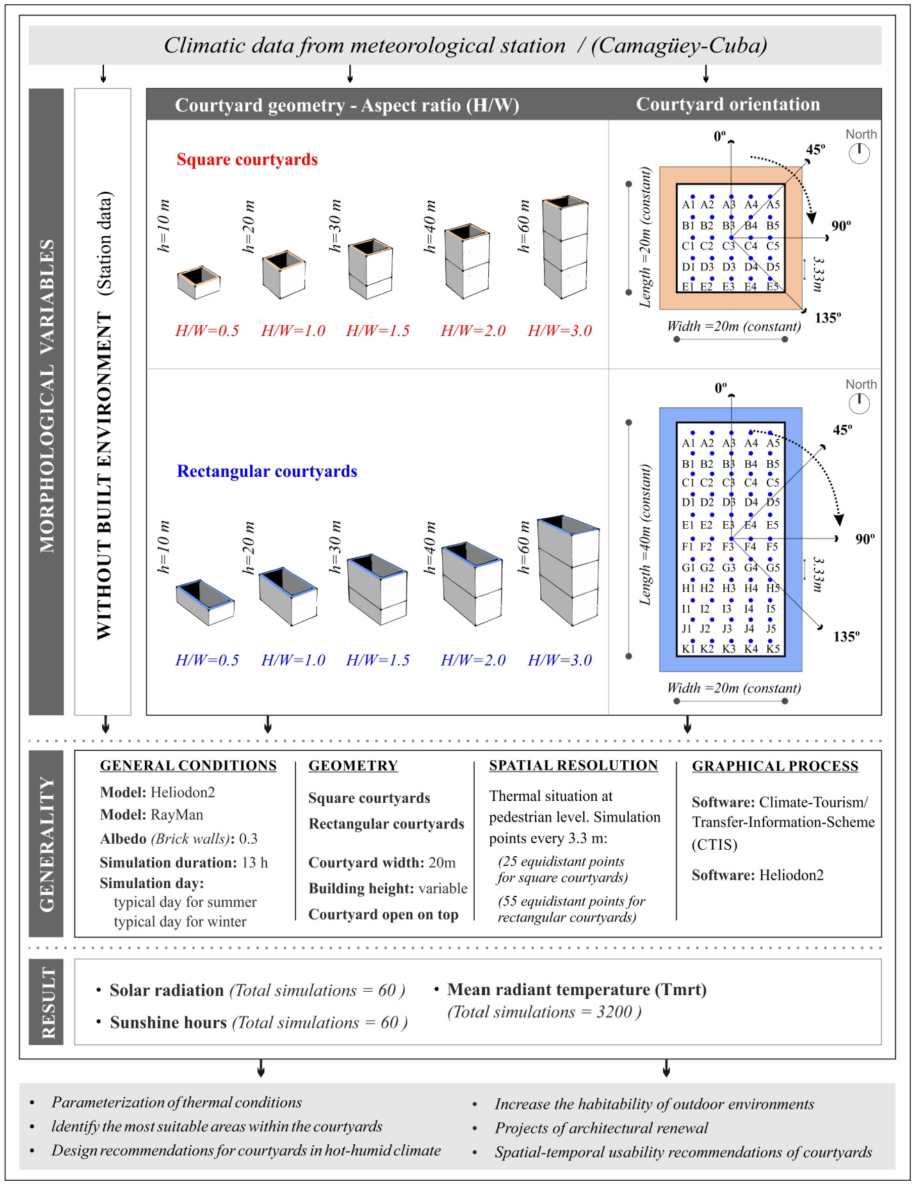


Fig. 3. Methodological framework.

foreseeing the validity of this study for the whole summer and winter period, the Tmrt was simulated considering average climatic values of these seasons. Consequently, the simulations were carried out for a typical summer and winter days, and it was possible to analyse the behavior of the Tmrt at different times of these days. Sunshine hours and cumulative solar radiation during summer and winter solstice were illustrated with Heliodon2, however, Tmrt were displayed using Climate-Tourism/Transfer-Information-Scheme (CTIS) software to facilitate the graphic compression of the results [64,65]. Besides, the time from 6:00 h to 18:00 was chosen to analyse the results.

3.3. Simulations and large courtyard model's description

The four religious complexes on the historical centre of Camagüey, Cuba (Fig. 1) were selected for this study. These courtyards have characteristics that differentiate them in the historical centre, such as aspect ratio and orientation. Consequently, the model settings are defined by courtyards open above and surrounded on all sides by internal building facades of equal height. Courtyards dimensions are 20 m by 40 m and 20 m by 20 m in the plan, corresponding to rectangular and square forms respectively. The simulations carried out assume that the maximum height for the surrounding facades was three times the courtyard width (Fig. 3). The aspect ratios were counted as 0.5, 1.0, 1.5, 2.0 and 3.0, assuming the width of 20 m. The model was rotated in steps of 45°, coinciding to N-S, SE-NW, E-W and NE-SW orientations. The surfaces are assumed to be made of brick and painted in light colour (typical albedo = 0.3). Vegetation was excluded in this study, considering its limited presence in the current courtyards of Camagüey.

RayMan model performs calculations on designated points, therefore, 25 and 55 analysis points were evenly distributed in square and rectangular courtyards respectively at a 1.1 m height. Different subzones are distinguished inside each courtyard, for more detailed analysis and recommendations for their potential usability for pedestrians, according to its thermal conditions during the day.

4. Results

4.1. Solar access analysis

Solar access is the most impactful parameter on Tmrt, especially in summer. In this regard, courtyards' geometries offer a wide spectrum of possibilities to regulate thermal conditions. As shown in Fig. 4, the cumulative solar radiation and sunshine hours are noticeably lower for rectangular courtyards elongated along the N-S axis, when compared to rectangular courtyards elongated along the E-W axis. Besides, the values obtained on NE-SW and NW-SE orientations are similar and show intermediate patterns between those obtained for N-S and E-W orientations. The spaces inside E-W courtyards receive direct solar radiation throughout most of the day during summer, mainly in the subzones next to the south side of the courtyard (points A5 to K5).

The graphs explicitly indicate that direct solar radiation increases with lower aspect ratios for all courtyard orientations. Increasing aspect ratios in E-W orientation has lower impact than in N-S orientation. This is the result of the closer proximity of the wall facing east and west in a courtyard elongated towards N-S axis, which produces more shading on the ground. Nonetheless, an improvement is possible for E-W orientation when aspect ratios are greater than 1.5.

The sunshine hours and the solar radiation values, between the subzones adjacent to the surrounded walls and the courtyard central subzone, are different. The most important variations occur on summer days. The subzones adjacent to the surrounding walls receive less sunshine hours, in comparison to the central area which is fully exposed to the sun. For E-W orientations, this

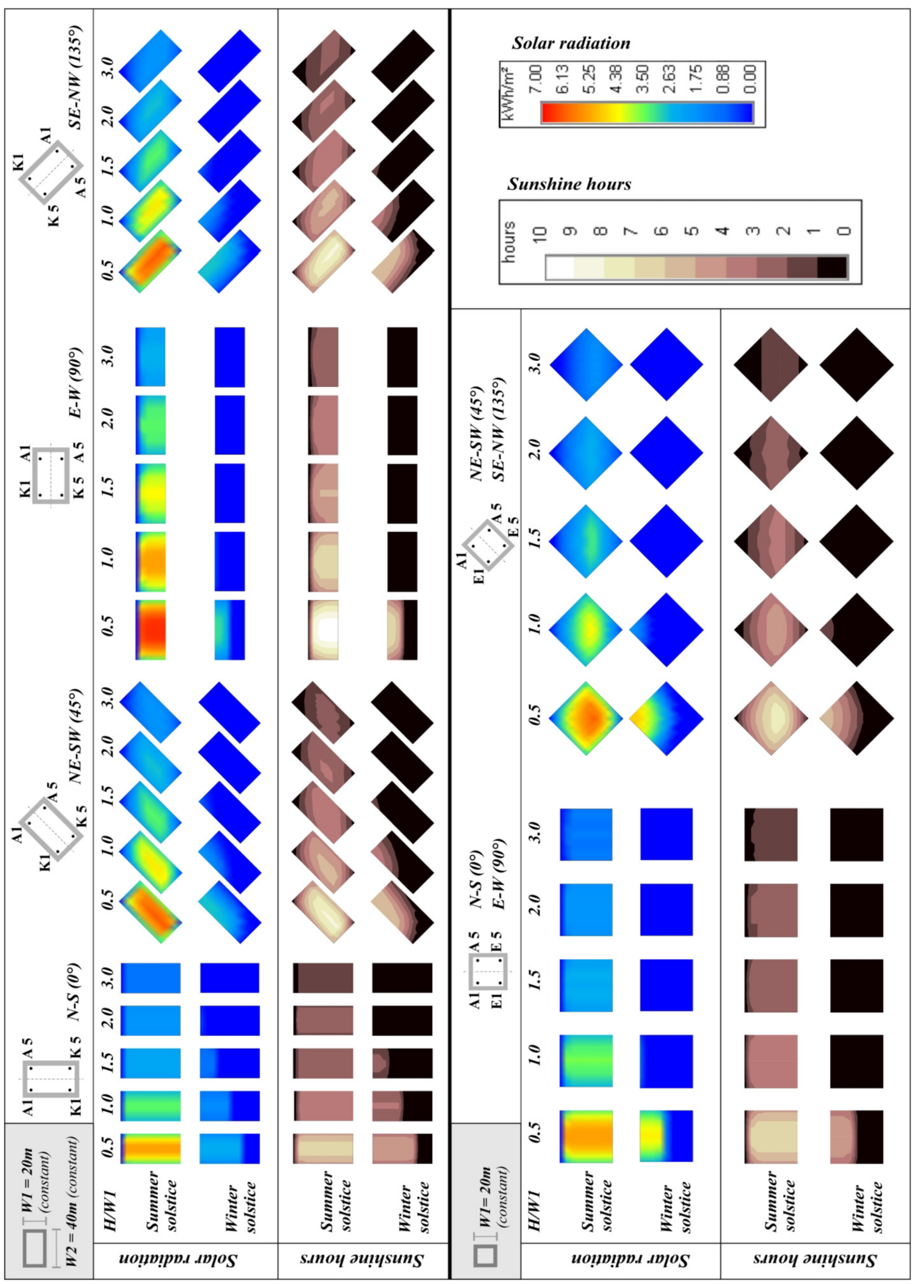


Fig. 4. Sunshine hours and solar radiation for different aspect ratios and orientations of courtyards - (winter and summer solstices).

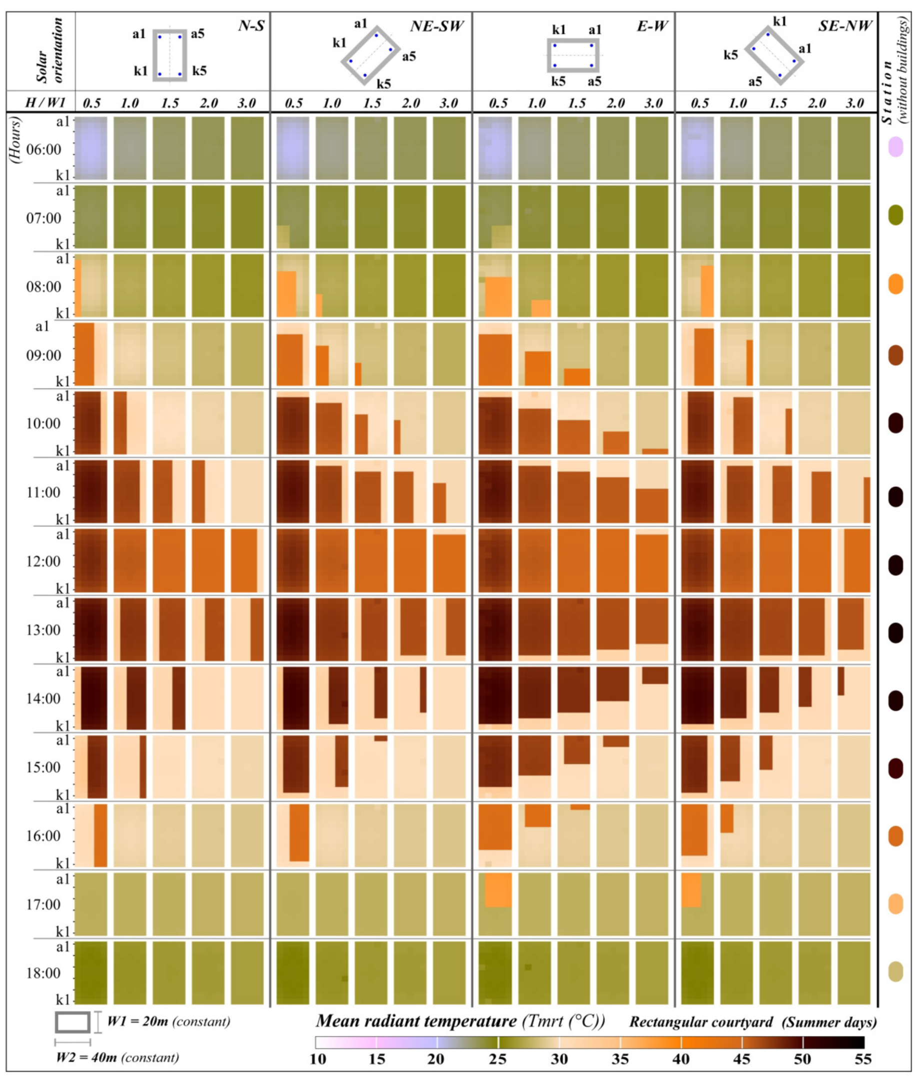
difference consists of around 9 h for low aspect ratios, while for high aspect ratios it is only of about 2 h. However, for N-S orientations this difference is of around 6 h and 1 h for low and high aspect ratios, respectively. From these findings, it appeared that during summer days, the subzones next to the north, east and west interior facades of the rectangular courtyards with N-S and E-W orientations receive a lesser amount of solar radiation than the other subzones inside the courtyard. In contrast, for the NE-SW and NW-SE orientations, the subzones adjacent to the surrounded walls are fully exposed to direct solar radiation. Besides, during winter days (where solar access is required), the most appropriate subzones for all simulated models are located on the northern half of the courtyard.

The distribution of solar radiation and sunshine patterns in square courtyards have a similar behavior to those obtained for rectangular courtyards. However, square courtyards have less sun exposure than rectangular ones, and offer better possibilities for solar control. In general, results related to the square courtyards are similar between N-S and E-W orientations, and between intermediate orientations (SE-NW and NE-SW). However, the most significant differences are perceived for E-W orientations, especially in summer days when, for 3 h, less solar radiation is incident on the central area of the square courtyards in comparison with rectangular courtyards.

4.2. Mean radiant temperature analysis

The resulting Tmrt during typical summer day continuously increased from 06:00 h to 14:00 h, while it decreased from 15:00 onwards for all rectangular and square courtyard models, irrespective of the aspect ratios and orientations (Figs. 5a, b and 6). Besides, the values of Tmrt are considerably high around noon, and follow similar patterns among the different orientations, in agreement with the results from the incident solar radiation discussed in the previous section. Considering the courtyards' thermal condition at critical hours (11:00 and 14:00), it is clear that almost all courtyard subzones are thermally uncomfortable, with Tmrt values above 40 °C. These results are expected, due to the high position of the sun in the summer solstice, the high intensity and long duration of the solar radiation, and the lack of solar protection from building elements or vegetation.

However, during winter days, the level of Tmrt is considerably



a)

Fig. 5a. a) Diurnal courses of Tmrt (° C) for rectangular courtyards with different aspect ratios and orientations - (typical summer day).

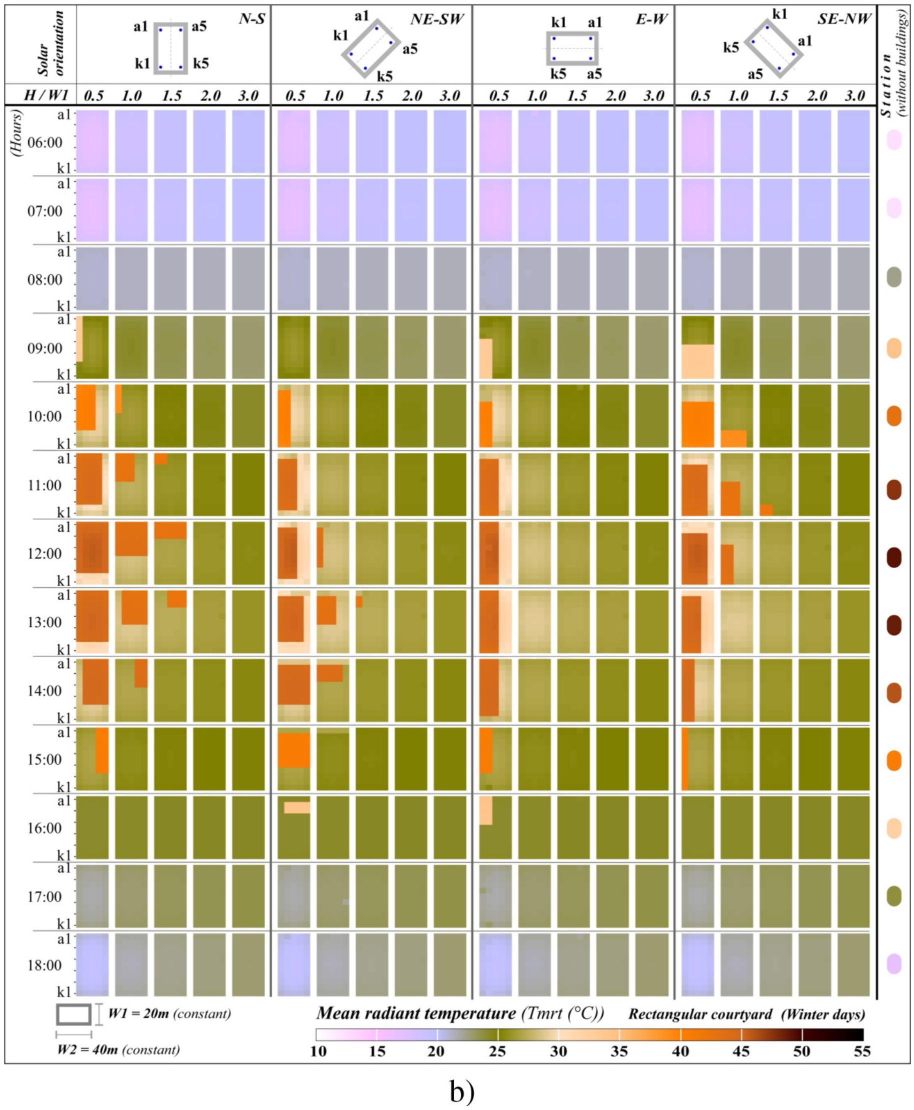


Fig. 5b. b) Diurnal courses of Tmrt (° C) for rectangular courtyards with different aspect ratios and orientations - (typical winter day).

lower than in summer days. Exploring the Tmrt behavior for all simulations performed during the daytime hours studied (from 06:00 to 18:00), it emerged that the maximum values recorded were 50 °C and 45 °C, for typical summer and winter days respectively. While the minimum values were found mostly in the mornings and oscillate around 21 °C for summer days and 17 °C for winter days.

The following sections (4.2.1, 4.2.2, and 4.3) summarize the most noteworthy results regarding courtyards' thermal conditions. Special emphasis is given to summer conditions, which are more representative and extend longer in the year, in comparison with the shorter and milder winter conditions in Cuba. The effects of geometrical configuration of courtyards (orientation and aspect ratio) and its implications into design and usability of outdoor environment are presented.

4.2.1. Effects of the aspect ratio of courtyard

The results show a clear reduction of Tmrt when courtyard walls -and aspect ratio-increase, particularly from 8:00 h to 11:00 h and from 14:00 h to 16:00 h. Nevertheless, the intensity and spatial distribution of Tmrt are similar and reaches its peak values from 12:00 to 13:00 h for all aspect ratios. For the case of aspect ratio H/W ≤ 1.0 the high level of Tmrt (≥45 °C) does not drop until 15:00 h and onwards due to the continuous exposure to the sun (Fig. 5a, b and 6).

In the summer, the increase in height of rectangular and square courtyards, leads to an increase on the area, with a Tmrt lower than 45 °C. Except for the most critical hours (11:00 till 14:00), Tmrt are lower than 30 °C. The increase of aspect ratio from 0.5 to 3 reduce in 100%, 75%, 45% and 85% the courtyard area with Tmrt higher than 45 °C at 11:00 h for N-S, NE-SW, E-W and SE-NW orientations respectively (Table 2). Therefore, the results show that Tmrt reductions due to the increase of aspect ratio are more effective for N-S orientations, while less effective for E-W orientations. When the solar relative position is high around noontime, the aspect ratio has little impact on Tmrt. In rectangular courtyards, with N-S orientation and high aspect ratio (H/W = 3), Tmrt lower than 45 °C are obtained for 20% of the area, while this area is only 10% for courtyards with E-W orientations (at noon). At 13:00 h, the change in aspect ratio from 0.5 to 3, reduce 60% and 28% the courtyard area with Tmrt above 45 °C, for N-S and E-W orientations respectively. For NE-SW and SE-NW orientations, this reduction is 45% and 35%

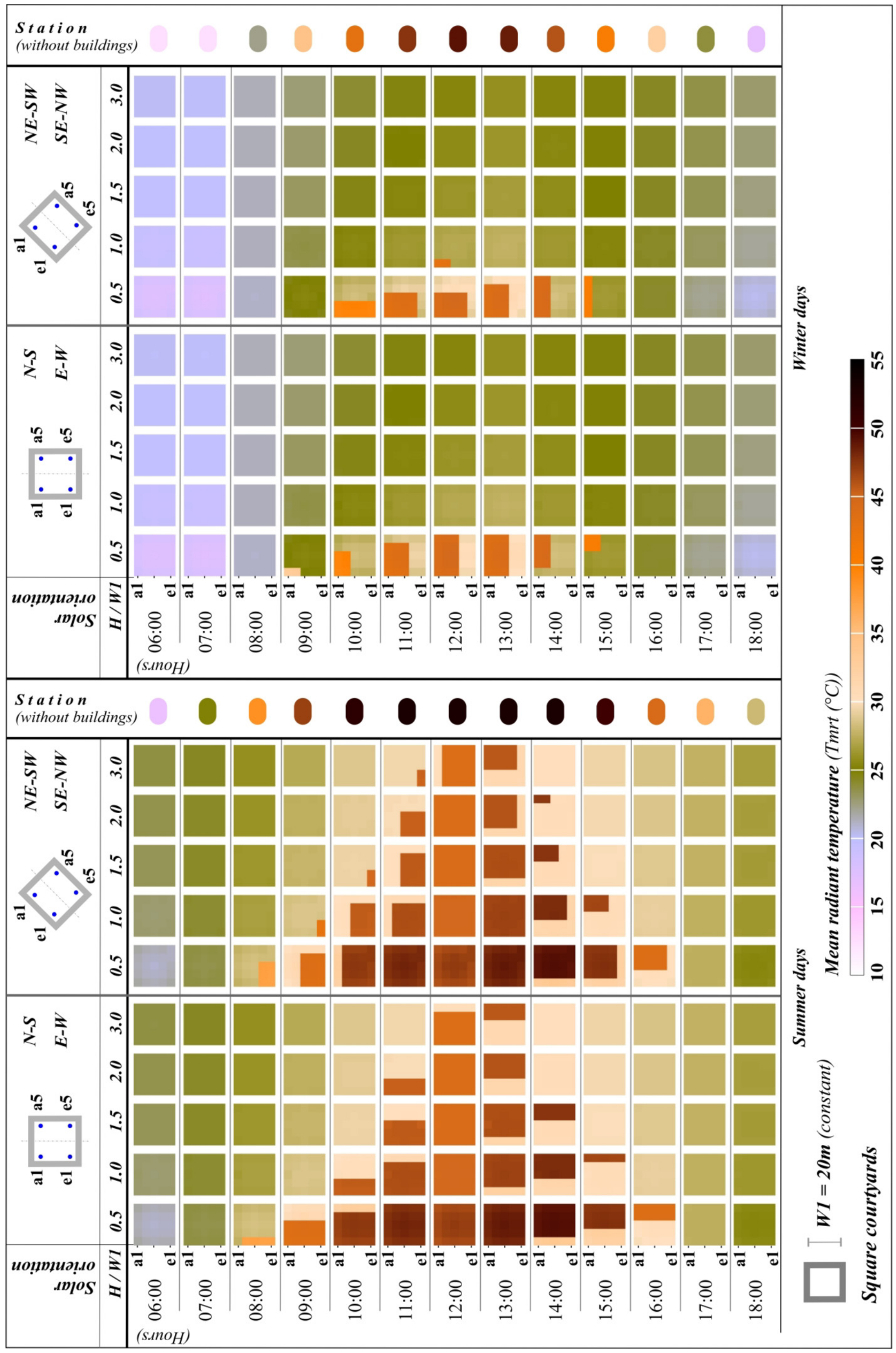


Fig. 6. Diurnal courses of Tmrt (°C) for square courtyards with different aspect ratios and orientations - (typical winter and summer days).

respectively. At 14:00 h the reductions of high Tmrt are more evident when changing aspect ratios from 0.5 to 3. These are 80% for N-S, NE-SW and SE-NW and 68% for E-W. However, in all orientations of square courtyards, changing aspect ratio from 0.5 to 3 produce a reduction of area with high Tmrt of 98%, 20%, 55% and 80% at 11:00 h, 12:00 h, 13:00 h and 14:00 h respectively (Table 2).

Additionally, Table 2 shows percentage of courtyard areas with PET values above 30 °C, corresponding to the thermal perception classifications for the ranges of heat stress. During the morning and the afternoon the conditions of heat stress (PET above 30 °C) are mitigated by high aspect ratios (H/W greater than 1.5). However, during critical hours (11–14 h) conditions of heat stress persist, even for high aspect ratios. These conditions are perceived in more than 50% of the courtyards area when the aspect ratio is less than 2.

4.2.2. Effects of the courtyard orientation

Results show that, at all the examined configurations, the highest values of Tmrt are generated in summer, when the long axis of the rectangular courtyards is along the East-West axis. However, it is explicitly shown that rectangular courtyards, elongated along the N-S axis, have less subzones with high Tmrt, when compared to the other orientations. Courtyards oriented NE-SW and SE-NW achieve lower and higher average Tmrt than courtyards oriented E-W and N-S respectively. Disregarding orientation, the number of

Table 2
Average percentage of areas with Tmrt ≥45 °C and PET ≥30 °C for summer day.

GEOMETRY	RECTANGULAR COURTYARDS																				SQUARE COURTYARDS									
ORIENTATIONS	N-S					NE-SW					E-W					SE-NW					N-S / E-W					NE-SW / SE-NW				
H/W	0.5	1	1.5	2	3	0.5	1	1.5	2	3	0.5	1	1.5	2	3	0.5	1	1.5	2	3	0.5	1	1.5	2	3	0.5	1	1.5	2	3
Percentage of areas with Tmrt ≥ 45 °C (summer)																														
Hours 9:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10:00	80	40	0	0	0	91	65	25	11	0	91	73	55	29	0	80	55	15	0	0	80	40	0	0	0	80	48	8	0	0
11:00	100	80	60	40	0	100	73	65	49	25	100	91	82	73	55	100	73	55	49	15	100	80	60	40	0	100	64	48	36	8
12:00	100	100	100	100	80	100	100	100	100	90	100	100	100	100	90	100	100	100	100	80	100	100	100	100	80	100	100	100	100	80
13:00	100	80	80	60	40	100	100	80	73	55	100	91	91	82	73	100	100	91	73	65	100	80	80	60	40	100	100	80	64	48
14:00	80	60	40	0	0	80	55	33	15	0	91	82	73	55	22	91	65	44	25	9	80	60	40	0	0	80	48	24	8	0
15:00	60	20	0	0	0	73	33	4	0	0	82	64	36	15	0	73	44	22	0	0	60	20	0	0	0	64	24	0	0	0
16:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average percentage of areas with PET ≥ 30 °C (summer)																														
Hours 9:00 - 10:00	60	0	0	0	0	65	25	7	0	0	82	44	22	0	0	55	15	0	0	0	60	0	0	0	0	48	8	0	0	0
11:00 - 14:00	100	80	60	40	0	100	73	65	49	25	100	91	82	73	55	100	73	55	49	15	100	80	60	40	0	100	64	48	36	8
15:00 - 16:00	60	20	0	0	0	73	33	0	0	0	82	64	36	15	0	73	44	22	0	0	60	20	0	0	0	64	24	0	0	0

subzones with high Tmrt are balanced around midday (12:00 h).

When the aspect ratio of courtyards is H/W = 0.5, no Tmrt variations are obtained, since most of the courtyard's surface is exposed to direct solar radiation. Only at 14:00 h, an increase of 11%, in the courtyard area with Tmrt higher than 45 °C, is observed for orientations E-W and SE-NW in comparison with the other two orientations (Table 2). On the other hand, when the aspect ratio is H/W = 3 the courtyard area with Tmrt higher than 45 °C is reduced in 100%, 75%, 45% and 85% for N-S, NE-SW, E-W and SE-NW orientations respectively. At 11:00 h, no area with Tmrt higher than 45 °C was observed for the orientation N-S, however for the orientation E-W, 55% of the courtyard area had Tmrt higher than 45 °C. For courtyard orientations NE-SW and SE-NW, Tmrt higher than 45 °C were observed in 25% and 15% of its surface areas respectively. At noon, 80% of the courtyard's area has Tmrt higher than 45 °C for N-S and SE-NW, while for other orientations this percentage increases to 90%. At 13:00 h, the E-W orientation has 73% of the courtyard area with a Tmrt higher than 45 °C, however, the area is reduced in 33%, 18% and 8% for orientations N-S, NE-SW and SE-NW respectively. At 14:00 h, Tmrt higher than 45 °C are obtained in 22% and 9% of the area in E-W and SE-NW courtyards respectively, while no high values are obtained for N-S and NE-SW (Table 2). In contrast to rectangular courtyards analysed above, the thermal pattern of square courtyards is similar for all orientations, therefore not showing significant variations in the area with Tmrt higher than 45 °C. By exploring the PET index with the variation of the courtyards orientation it is perceived that the N-S orientation offers better possibilities to mitigate the stress by heat. Conversely, for the E-W orientation the conditions of heat stress are more critical in time and space.

4.3. *Design and usability recommendations for large courtyards*

4.3.1. *Geometrical design recommendation*

From a geometrical point of view, the aspect ratio has a larger impact on the thermal behavior of the courtyard when compared with the orientation of the courtyard. Increasing the aspect ratio clearly has a stronger impact on the spatial-temporal distribution of Tmrt inside the courtyards, significantly increasing the area with Tmrt lower than 45 °C, during the summer. However, courtyard orientation is more influential in the distribution of shaded areas. Therefore, a set of ratios are recommended to achieve an efficient performance of courtyards in both summer and winter. Rectangular and square courtyards with orientations N-S and NE-SW show better thermal conditions. The worst thermal conditions are obtained in courtyards with an E-W orientation. Aspect ratios higher than 1.5 help improving thermal conditions inside courtyards during summer, otherwise additional shading elements are necessary.

4.3.2. *Spatial-temporal usability of the courtyard subzones*

Overall, findings show that the number of hours with acceptable thermal conditions (Tmrt < 45 °C) could be extended to all diurnal hours, except for the critical period between 11:00 h to 14:00 h in summer (this period is reduced to 12:00 h to 13:00 h in courtyards with high aspect ratios). During this time, the use of the courtyards is not recommended, especially those with a low aspect ratio. Additional solar protection elements are crucial, to increase shaded areas and therefore, thermal comfort. Before and after the critical time, the courtyard can be used, particularly the shaded areas. However, during the coolest days of the winter using the courtyard around noontime could be acceptable.

As a general rule, during the critical time (between 11:00 h and 14:00 h), particular subzones of the courtyard, adjacent to the surrounded facades, are more comfortable than the central subzone. During the summer mornings, the east side of N-S and E-W courtyards has a better thermal condition. However, for NE-SW and SE-NW orientations, the subzones next to the facades oriented NE and SE are the most thermally favourable. During the afternoon, the areas closer to the facades facing W are most favourable when the courtyard axis is oriented N-S and E-W. For courtyard orientations NE-SW and SE-NW, subzones next to NW and SW facades have a

more favourable thermal behavior.

4.4. Application of the recommendations in the large courtyards of Camagüey

Derived from the results that were obtained, this section aims to propose several recommendations related to the use of three of the selected courtyards as case studies. Since the focus is on the impact of courtyards morphology on thermal conditions these three courtyards are selected due to their higher compatibility with the geometrical and landscape characteristics of the simulated models in comparison with the Merced courtyard. In addition, the Merced courtyard has plenty of vegetation, a design feature not considered in this study. In the three cases, a large number of peoples use the courtyard for recreational, cultural and leisure activities. The recommendations do not necessary apply to individuals, since people tend to choose the most shaded and thermally comfortable area by themselves, without the need of advice. Therefore, the recommendations given in Fig. 7 are mostly useful when planning outdoor activities for a large group of people and for defining design retrofitting strategies in large courtyards, according to the spatial distribution of the Tmrt.

As a general rule for summer days, outdoor activities in unshaded areas are not recommended between 10:00 h and 15:00 h. Therefore, the provision of shade, by means of canopies and vegetation, is necessary if outdoor activities are to occur during this time of day. For the San Juan de Dios and Pías School courtyards, the most comfortable subzones between 10:00 h and 15:00 h, are those adjacent to the surrounding interior walls. Shading elements are therefore recommended in the central subzones. On the other hand, for the courtyard of Convent of Carmen, the shading elements should be located in the eastern subzones, since this area is the most uncomfortable in the afternoon. In the morning, the most comfortable area is on the eastern side. For winter days, it is

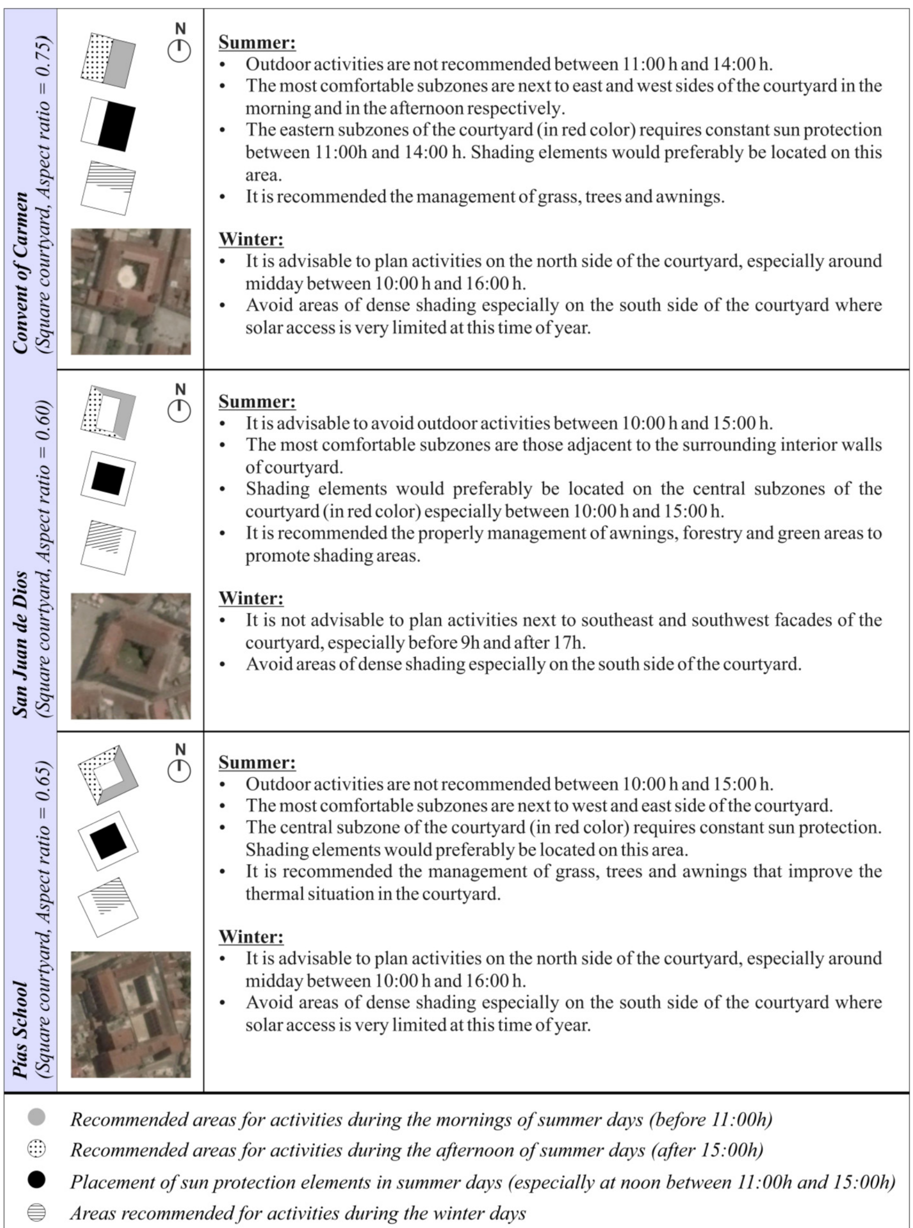


Fig. 7. Implementation of the design recommendations and usability in three large courtyards in Camagüey, Cuba.

advisable to plan activities in the north subzones of the three courtyards, especially between 10:00 h and 16:00 h. Also, it is recommended to avoid areas of dense shading, especially on the south side of the courtyard, where solar access is very limited at this time of the year.

5. Discussion

Calculating the average daily Tmrt shows that blocking the direct radiation, by increasing the aspect ratio of courtyards, can be highly influential in improving thermal conditions, as a result of creating larger shaded areas. Similar to the results reported by Ref. [15], our findings highlighted that among all geometric parameters studied, the height of the walls surrounding the courtyards with fixed floor dimensions is found to be the most influencing parameter on the outdoor thermal environment. This is in agreement with the studies from Refs. [4,12,26,27]. However, similar to [25,51], our research also shows that increasing the height of the walls is insufficient for improving thermal conditions at noontime. This highlights the need to look into bioclimatic strategies for providing comfortable spaces, such as the application of shading devices or greeneries for hot-humid climates [27]. Besides, our findings point out some aspects also recommended by Ref. [26]. For example, the optimum aspect ratio in summer is that which provides the maximum shaded area, whereas in winter it is that which allows a certain exposure to the sun. Hence, high and relatively narrow courtyards are recommended for summer days, while in winter they should be expanded and low. For permanent structures, especially ones with heritage value, this represents a challenge for architects, most of the time, impossible to achieve. Therefore, for new courtyard buildings or in the renovation of non-historical buildings, designing courtyards with aspect ratio values ranging between 1 and 3 is recommended for warm-humid climates, providing a certain level of wind permeability through the surrounding walls, for an efficient ventilation. For historical courtyard buildings, other non-invasive design strategies should be implemented, as those provided above, for the three selected courtyards in Camagüey. Regarding courtyard orientation for rectangular courtyards, our results also suggest that orienting the long axis as close as possible to the north–south is desirable to achieve a reasonable performance in agreement with [26]. However, this orientation is not the most convenient for east and west facades facing the courtyard. Therefore, in these cases, appropriate shading devices should be incorporated for those facades.

The methods presented here can be applied to similar researches in other climatic zones, and provide valuable information for architects and urban planners, however, it is important to account for the limitations of this study. An important aspect to be considered, when analyzing thermal conditions in courtyards, is the influence of courtyard geometry on wind flow, which can reduce or increase the Tmrt values. In the case of this study, the effect of wind flow is rather limited due to the central location of the studied historic area, in the centre of Camagüey. The surrounding urban areas reduce the penetration of wind in their interior, due to the increased surface roughness [66], however the importance of wind should also be considered. Furthermore, the radiation model in RayMan model does not include the heat storage in the facades of buildings, and does not consider multiple reflections between buildings. However, the latter limitation is less important for low aspect ratio courtyards. Simulations were run in a sunny day with clear sky, while the sky in the tropics can be cloudy, especially in summer afternoons, which can result in a lower level of Tmrt. Besides, for more accurate results, a regional validation of this Model should be performed through actual field studies and measurements in Cuba.

6. Conclusions and future developments

The geometrical characteristics and orientation of courtyards impact their thermal conditions, especially in warm-humid and compact city centers, such as is Camaguey's in Cuba. Based on numerous simulations and analysis of solar radiation and Tmrt, this paper proposes general recommendations for the optimization of thermal conditions and on the usage of courtyards in warm-humid regions, with a similar latitude as Camagüey, Cuba. The most noteworthy insights and their implications to ameliorate courtyards thermal conditions are summarized as follows:

a) Results confirm the impact of increasing the aspect ratio in courtyards and change their axis orientation on the thermal conditions. The duration of excessive direct solar radiation increases with low aspect ratios ($H/W < 1.5$) and for the cases with axis orientations close to E-W. From the analysed cases, square courtyards receive less solar irradiation than rectangular ones. Besides, the subzones adjacent to the surrounding walls receive direct solar radiation during shorten time than the central area.
b) Aspect ratio has a stronger impact on the thermal conditions in courtyards than orientation due to the greater spatial-temporal variability of Tmrt, when changing the courtyard's wall height. The variation in the amount of area with Tmrt higher than 45 °C can be twice as large when changing the courtyard's aspect ratio from 1 to 3, in comparison with the changing of its orientation. However, the orientation has a stronger impact on the distribution of shaded area.
c) A set of orientations and aspect ratios are recommended to improve thermal performance of courtyards in both summer and winter seasons. Better thermal conditions are obtained in courtyards with orientations N-S and NE-SW. Orienting the courtyard's long axis away from the E-W results in a lower Tmrt in around 1/2 the area of a courtyard with high aspect ratio ($H/W = 3$), especially between 11:00 h and 13:00 h. The Tmrt reduction can reach up to 15.7 °C. Besides, increasing the aspect ratio of courtyards noticeably decreases the level of Tmrt during diurnal hours. Courtyards with an aspect ratio of $H/W = 3$ can achieve a reduction of Tmrt of 20 °C when compared with an aspect ratio of $H/W = 0.5$. In addition, the subzones in the courtyard where the Tmrt is above 45 °C can also be reduced by 100% with high aspect ratios. Therefore, aspect ratios lower than 1 are not recommended, unless they are provided with sun shading elements in their central areas.
d) During summer days, courtyards in the warm-humid climate of Cuba can provide comfortable conditions before 11:00 h and after 14:00 h. These periods could be increased once the courtyard's thermal performance is adjusted through adequate design strategies. In the morning, the east side of N-S and E-W courtyards have better thermal condition. Subzones near the northeast and southeast sides are recommended on NE-SW and SE-NW courtyards. In the afternoon, the west side of N-S and E-W courtyards are recommended. Moreover, subzones near the northwest and southwest sides have better thermal condition for NE-SW and SE-NW courtyards, with Tmrt values lower than 45 °C.

This study is limited to the courtyard's thermal conditions in terms of Tmrt and also to a partial analysis of the PET index for the simulated models. The values of PET are preliminaries from the effects of courtyard aspect ratio and orientation, and may vary due to the modification on wind conditions. The results obtained contribute to provide design and renovation recommendations to

reduce heat stress conditions inside courtyards in warm-humid climates (especially in Cuba), and consequently to reduce UHI effects and promote more comfortable urban environments. Ameliorating courtyard conditions thought passive solar design is an effective low-energy strategy to improve indoor thermal conditions on spaces facing the courtyard in most climates and urban morphologies. Future research is needed to explore the impacts of courtyards' aspect ratios and orientations on the wind conditions and on the thermal comfort inside the surrounding buildings during daytime and nighttime for the whole year. Specific aspects of courtyards design (e.g. vegetation, surface materials, albedo and emissivity) also need to be incorporated to provide more holistic recommendations.

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